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Chapter 20: Pecan

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Chapter 20
Pecan

Tommy E. Thompson and Patrick J. Conner

Abstract The pecan, *Carya illinoinensis* (Wangenh.) K. Koch, is the most economically important member of the *Carya* genus and is the most valuable native North American nut crop. The *Carya* genus is a member of the walnut family, Juglandaceae, and comprises 20 species. Over 98% of the world's annual pecan production is produced in the southern USA and northern Mexico. Pecan is a diploid ($n=16$), monoecious, long-lived tree species. Owing to its heterodichogamy, pecan is primarily cross-pollinated, resulting in high heterozygosity with severe inbreeding depression when selfed. Establishment of commercial pecan orchards during the nineteenth century was mainly by planting open-pollinated nuts from mother trees possessing desirable characteristics. These orchards consist of trees with widely varying production and quality attributes due to the heterozygosity of pecan. Vegetative propagation became popular ca. 1900, and most newly planted orchards consist of a chosen combination of clonally propagated superior varieties. Clonally derived orchards are more productive and produce nuts of much higher quality than remaining native or seedling orchards. Thirteen *Carya* species, including pecan, are native to the USA. The National Clonal Germplasm Repository for Pecans and Hickories which preserves over 300 pecan cultivars, landraces, and species accessions was established in 1984 to describe and preserve this underutilized resource. Objectives of pecan breeding are higher yields and nut quality, and resistance to diseases and insects. Pecans are attacked by a wide range of disease and insect pests causing substantial losses to the crop. Various levels of resistance to scab and aphids are available in improved pecan varieties, and breeding programs are focusing on developing new cultivars with high levels of resistance in combination with good

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horticultural attributes. Another major effort in pecan breeding is the development of earlier maturing cultivars with the potential to bear more consistently over years.

Keywords Pecan • Breeding • Genetics • Host plant resistance • Insect resistance • Disease resistance • Trees • Nuts • Hickory • Plant selection • *Carya illinoinensis*

1 Introduction

The pecan, *Carya illinoinensis* (Wangenh.) K. Koch, is the most economically important member of the *Carya* Genus, and is the most valuable native North American nut crop. Pecans are harvested from "native" trees throughout the natural range of the species (Fig. 20.1). The culture of "improved" trees has extended considerably beyond the native range; from Ontario, Canada, south to Oaxaca, Mexico, and from the Atlantic coast of Virginia and the Carolinas west to California (Fig. 20.2) In addition, the pecan is grown commercially to a minor extent in Israel, South Africa, Australia, Egypt, Peru, Argentina, and Brazil.

Over 98% of the world's annual pecan production is produced in 15 US southern states and northern Mexico (Pena 2007). This North American annual production averaged 176,443 metric tons (in shell basis) for 1998–2005. Mexico produced about 35% of this, followed by Georgia (19.2%), Texas (14.2%), and New Mexico

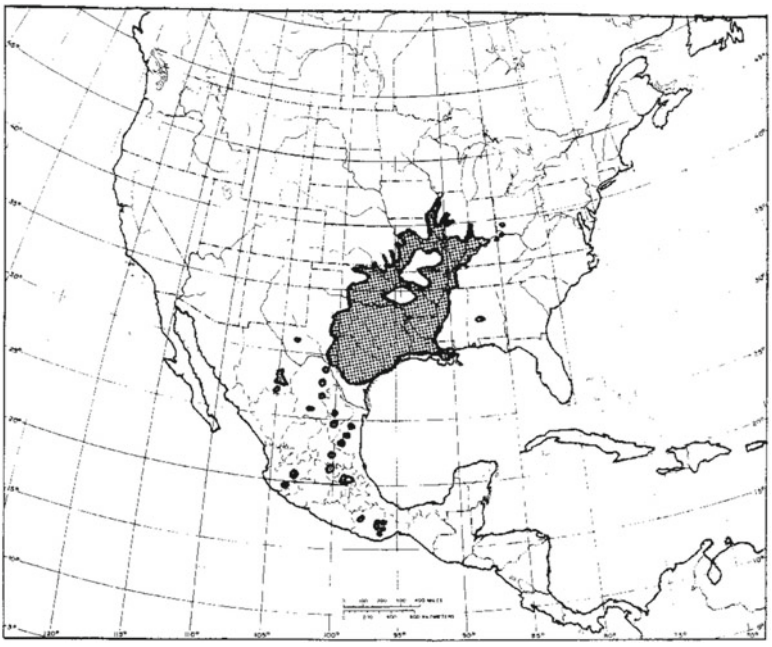

Fig. 20.1 Native pecan distribution (Grauke and Thompson 1996)

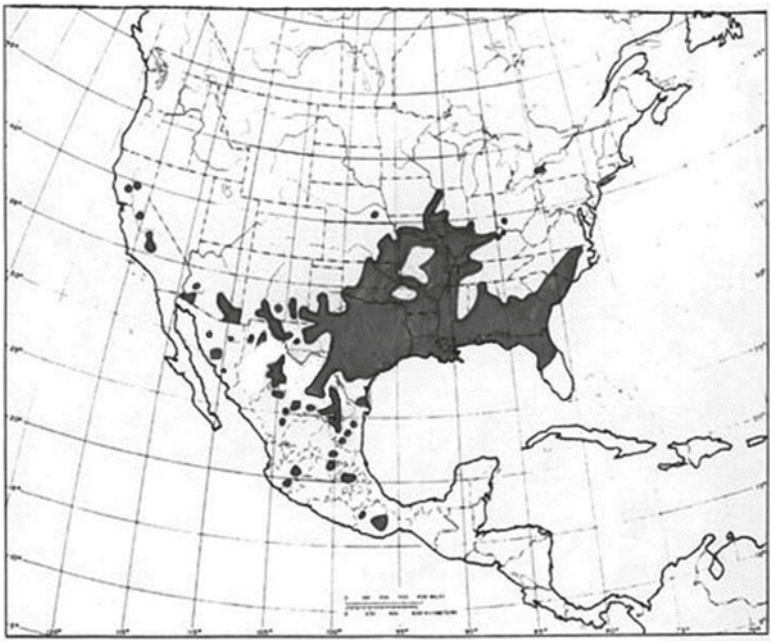

Fig. 20.2 Commercial pecan production in America (Grauke and Thompson 1996)

(12%). The total US production average for 1991–2001 was 121,545 metric tons. The production dropped to 104,682 metric tons for 2002–2005 (Pena 2007). Major recent production challenges such as disease problems in Texas and Georgia, hurricanes along the gulf coast, and droughts limited global production.

The *Carya* genus is a member of the walnut family, Juglandaceae, and comprises 20 species (Grauke and Thompson 1996). Thirteen *Carya* species, including pecan, are native to the USA. Of all *Carya* species, seven are reportedly cultivated for their nuts (Grauke and Thompson 1996), but pecan is the only economically important crop. Selection of superior genotypes and limited horticultural use has been made of two other species in North America: shagbark hickory [*C. ovata* (*Mill*) *K. Koch*] and shellbark hickory [*C. laciniosa* (*F. Michx.*) *Loudon*]. Culture of both shagbark and shellbark hickories is restricted by their long juvenile periods (>10 years) and low yields of hard-to-shell nuts. The Chinese reportedly cultivate some of their hickories for food to a small degree.

Many hickory species, including pecan, have a deserved reputation of producing tough useful wood for tool handles, flooring, veneer, among other products. Hickory wood is also much prized for use in smoking meats because of the distinctive flavor it imparts on the product. Because hickories are slow to grow to an economical size, naturally occurring trees are harvested for wood rather than plantation trees. As a result, the best specimen trees are often preferentially harvested, depleting the genetic potential of these populations over time.

Pecan is grown in a wide range of environments ranging across the arid Southwest, the humid Southeast, and the variable Midwest. Each of these geographic regions places unique environmental constraints on the cultivars that can succeed there. In addition, pecan culture has become more complex with the recent adoption of improved orchard techniques such as hedging and other forms of tree control and mechanical thinning of excess crop load. No single cultivar can meet all the requirements the industry now places on them. Instead, there is an increased demand for an array of regionally and horticulturally adapted cultivars. Orchards of inferior older cultivars or poorly adapted new cultivars are continually abandoned or updated with more profitable cultivars. A review and update of the current genetic status of this crop is needed since breeding objectives have become more refined, and available methods of genetic plant improvement have expanded.

2 Origin and Domestication of Scion Cultivars

Establishment of commercial pecan orchards during the nineteenth century was mainly by planting open-pollinated nuts from mother trees possessing desirable characteristics. Trees that produced large nuts with thin shells were especially prized by early growers for seedstock as this combination of traits greatly decreased the workload of obtaining the edible kernel, a process that was done by hand (Corbett et al. 1926). Other traits selected include resistance to scab disease, early maturity, and heavy yields (Taylor 1906, 1907). This system facilitated genetic improvement of cultivated germplasm since each tree in the orchard was genetically different, and superior trees were identified each cycle of growth. Seed from these superior trees could be used to establish the next orchard, and so on. Thus open-pollinated half-sib populations existed until clonal propagation of superior genotypes led to the widespread use of true cultivars. Currently, the few remaining seedling orchards in the Southeast, some of which have been abandoned, are being examined by researchers in the hopes of discovering genotypes with a high degree of insect and disease resistance (Goff et al. 1998).

The term cultivar was poorly defined early in the industry. Although experienced growers knew it not to be true, a large influx of new growers and a limited understanding of genetic science led to belief that pecan seed would come true to the female parent. This belief persisted in some locations even into the early twentieth century (Halbert 1909). This erroneous concept was disproved as seedling orchards began to bear and the variability of the nut characteristics of the seedlings became evident. Once improved methods of budding and grafting became widespread, the concept of a scion cultivar being a clone instead of an open pollinated collection of mainly half-sib trees was accepted. From that point on, vegetative propagation essentially established what a cultivar was in pecan production. This development allowed more accurate selection of superior pecan material since genetic variability of the scion was eliminated among tested trees, and environmental variability could be more adequately defined. Clonal propagation also vastly improved the uniformity and quality of the harvested crop, while simplifying management and nut processing.

Early clonal propagation of pecan essentially followed ideology common to pomology, but consistent success requires greater care and attention to details than in many other species. Many early pecan growers propagated favorite trees on a small scale with no record of their achievement. The first documented success was that by Abner Landrum of Edgefield, South Carolina in budding pecan scions onto hickory stocks in 1822 (True 1919). Later, in 1846, a slave gardener named Antoine propagated an orchard of 'Centennial' pecans at Oak Alley Plantation in Louisiana. The first record of a nursery selling grafted pecan trees was that of William Nelson of New Orleans, who began selling grafted trees in 1879 (Crane et al. 1937). E.E. Risien of San Saba, Texas developed a ring budding technique in the 1890s that increased the supply and decreased the price of grafted trees, precipitating an active period of pecan nursery sales and orchard establishment (McHatton 1957; Wood et al. 1990).

The period from the 1890s to 1930s was one of rapid proliferation of named clonally propagated pecan cultivars. The new-found ease of propagation allowed the owners of supposedly superior trees to attach a name, often the owner's, and propagate trees locally. This was an exciting era in pecan history because new orchards were being planted on a large scale and beginning to come into production. Also of note, the value of plant breeding and plant improvement in general was filtering down to the growers, and generating much enthusiasm for the use of new "improved" cultivars. Unfortunately, new cultivars were often developed after observing only a few years production of the parent tree, and were of dubious horticultural merit. Thompson and Young (1985) documented over a thousand pecan cultivars which have been listed over the years, and there are likely many more. Most of these were never widely popular and are now extinct, but a few exceptional cultivars from this period still comprise a major portion of current orchards. The latest national cultivar inventory (Thompson 1990) showed that 'Stuart,' which was first propagated in 1886, made up almost one quarter of all trees in USA grafted or budded orchards (Table 20.1). Approximately half (47.3%) of the improved trees in the USA consisted of three cultivars: 'Stuart' (22%), 'Western Schley' (14.6%), and 'Desirable' (10.9%), which were all developed in the late nineteenth or early twentieth century. Of the top 33 cultivars mentioned above, 5 are clones selected directly from native stands. Most others are only two or three generations from native parentage.

The original 'Stuart' tree was selected from seed from an Alabama seedling, while 'Desirable' was grown and selected by a nurseryman in an early breeding effort (Thompson and Young 1985).

These figures strongly reflect the permanence of pecan orchards and the understandable reluctance of growers to replace older trees with superior newer cultivars due to the nonproductive establishment years. An additional barrier to the adoption of new cultivars is the paucity of long-term yield data for new cultivars. The large size and long life-cycle of pecan place strong limits to the scope of cultivar trials that can be reasonably conducted. Planting new cultivars requires a leap of faith on the part of the grower that recently released cultivars that are successful in academic trials will do well as mature trees in his location. Mistakes in cultivar choice will require that the grower either replace the trees and once again endure the nonproductive establishment years, or adapt to the new cultivars' faults as best they can.

Table 20.1 Estimated hectares and percent of each cultivar in the USA (Thompson 1990)

Cultivar	Hectares	%	Cultivar	Hectares	%
Stuart	47,703	21.8	VanDeman	877	0.4
Western Schley	31,848	14.6	Maramec	830	0.4
Desirable	23,849	10.9	Cherokee	809	0.4
Wichita	22,168	10.1	Tejas	809	0.4
Schley	11,696	5.4	Delmas	767	0.4
Cheyenne	10,498	4.8	Sumner	735	0.3
Success	5,550	2.5	Barton	722	0.3
Cape Fear	4,786	2.2	Frotscher	707	0.3
Moneymaker	4,295	2.0	Elliott	682	0.3
Mohawk	3,099	1.4	Pabst	668	0.3
San Saba Imp.	2,873	1.3	Caddo	617	0.3
Mahan	2,856	1.3	Teche	615	0.3
Moore	2,825	1.3	Burkett	526	0.2
Choctaw	2,549	1.2	Shoshoni	454	0.2
Kiowa	1,788	0.8	Mobile	398	0.2
Sioux	1,649	0.8			
Ideal	1,097	0.5	Other	26,019	11.9
Chickasaw	1,084	0.5			
			Total	218,449	100.0

For this reason, many growers continue to replant with cultivars that they are familiar with even when new superior cultivars appear to be available.

Pecan trees are cultivated over a wide geographic area spanning from California to Virginia, and contributes to the economy of 24 states (Wood et al. 1990). Pecan production can be separated into four broad regions: the southeastern spanning from Virginia to Louisiana and Arkansas, the south central consisting of east and central Texas and southern Oklahoma, the northern containing northern Oklahoma and the Midwest, and the west which includes far west Texas and southern areas of New Mexico, Arizona, and California. Each of these production regions has environmental and economic constraints which must be met by the cultivar to be successful. Not surprisingly, orchards in each region consist of different sets of cultivars. In many cases, cultivars which are successful in one region cannot be grown profitably in other regions. Breeding programs must, therefore, target new cultivars to the regions and uses to which it is best adapted.

The southeastern region is typified by a long growing season with humid summers. Pecan scab, *Cladosporium caryigenum* (Ell. et Lang.) Gottwald (1982), is a fungal disease that infects pecan leaf and nut shuck tissue when they are wet. Commercial pecan plantings may require up to 11 fungicide applications annually to control the disease (Ellis et al. 2000). The frequent rainfall in this region during the growing season makes resistance to pecan scab a necessity in successful cultivars. Highly susceptible cultivars such as Wichita and Western Schley, which are extremely productive in the southwest, are not productive in normal years in the Southeast even with the use of fungicide sprays. The most profitable cultivars in this region mature their nuts early in the season (mid September to early October)

allowing them to be processed in time for the holiday gift-pack trade (Sparks 1992). Historically, most successful cultivars in this region have moderate crop loads and a less pronounced alternate bearing intensity (Conner and Worley 2000). However, the adoption of mechanical fruit thinning may allow fruit loads to be adjusted so that cultivars which set heavier crops can be successful here in the future.

Two cultivars, Stuart and Desirable, make up over half of the mature trees in commercial orchards in Georgia (Florkowski et al. 1999), where the majority of the production lies in this region. 'Stuart' continues to be popular as a mature tree in Georgia, but new plantings have decreased due to its low precocity and inadequate kernel percentage. 'Desirable' is currently the most popular commercial cultivar in Georgia and comprised 49% of the trees planted in 1993–1997. 'Desirable' sets the standard for nut quality in the Southeast, but requires excellent cultural practices to perform well, and has also become increasingly more susceptible to pecan scab. A range of other cultivars are being planted in this region (Wells 2007), but no cultivar combines all the attributes of large nut size, early harvest date, high kernel quality, and scab resistance that is desired.

In the arid environments of the western region rainfall in the summer is sparse, and fungal diseases are a minor concern. This region has high light intensities and orchards managers often use mechanical pruning techniques to maximize light infiltration of the canopy. Because harvest in this region is later than that of the southeast, cultivars must be able to maximize production to make up for the lower prices received. This region has a shorter growing season, and early freezes can be a problem. Orchards in this region are often composed of 'Western Schley,' with 'Wichita' as a pollinizer. Both of these cultivars are capable of producing a high yields. 'Western Schley' was developed in the early twentieth century, and is popular because of its profuse branching which responds well to pruning, and it is less susceptible to zinc deficiency and water stress (Byford 2005). 'Wichita' is the most productive pecan cultivar ever developed, but requires optimum management to fulfill its potential (McEachern and Stein 1997).

The south central region is a transition zone between the southeastern and western regions. Scab resistance becomes a more important factor in cultivar choice as you move from western Texas to the south and east. 'Desirable,' 'Pawnee,' 'Wichita,' and 'Western Schley' are all grown in this region. Some very productive cultivars with high nut quality have been developed by the USDA for this region.

Older inferior cultivars lacking in productivity, nut quality, and disease and insect resistance are being replaced with superior newer cultivars. In central Texas, for example, 'Wichita' routinely out yields 'Western Schley,' producing at least twice as much kernel weight per acre (Thompson et al. 1981; Thompson and Hunter 1983). 'Pawnee,' released by USDA in 1984 (Thompson and Hunter 1985), is currently the most popular cultivar being propagated worldwide, probably followed by 'Western Schley,' 'Wichita,' and 'Desirable.'

The northern production region requires cultivars that have trees that are resistant to winter injury and can mature their fruits in a shorter growing season. Cultivars suited to this region generally have smaller sized nuts, which is a characteristic of most early maturing nuts (Sparks 1992). Most northern adapted cultivars also do not

have the productivity of the southern cultivars. Cultivars can be chosen for either the in-shell market or the shelling market. The in-shell market is a direct market to the consumer, and requires a larger nut with an early harvest. When nuts are sold for the shelling market, size is less important than a good kernel percentage. Cultivars grown in the most northerly regions generally consist of selections from native stands which possess superior nut size and kernel development. Cultivars in the more southern end of this region are more likely from breeding programs. Recent USDA releases with northern adapted germplasm in their pedigree ('Pawnee,' 'Kanza,' 'Osage,' and 'Lakota') are currently gaining popularity in this region.

3 Genetic Resources

Louis D. Romberg, a former ARS pecan breeder, began a pecan and hickory collection in the 1930s at Brownwood, Texas to have parental material to use in the pecan breeding program. The collection of pecan cultivars and other clones were grafted to trees. This collection was designated the National Clonal Germplasm Repository for Pecans and Hickories in 1984, and a Crop Germplasm Committee was formed. Native pecan collections have since been added, as well as many clones of other *Carya* species. Presently, the Cultivar Collection maintains over 300 pecan cultivars as live trees, and nut specimens of many additional cultivars are also preserved. This collection represents all pecan growing regions of the USA and is the largest collection of pecan cultivars in the world. Supporting records of accession origin and characteristics are also available. Live accessions are maintained as grafted trees, targeting two trees of each cultivar at the Brownwood site, and duplicate collections at College Station, Texas. Accessions are provided upon request to researchers, and are provided to private growers when commercial nurserymen cannot provide propagation wood of a clone. Accessions are distributed as graftwood (typically five double graft sticks per accession) in January and February. In addition, seed is occasionally distributed from particular accessions for establishment of seedling rootstocks for subsequent grafting. Nut voucher specimens are maintained for each tree to verify identification. Additional nut samples from other orchards are maintained for many cultivars to provide a sample of the variation that exists across locations. This *ex situ* collection provides an abundance of readily available, verified, and well-documented plant materials for use in biochemical and molecular characterizations. Verified inventories of some pecan cultivars have been characterized with isozyme analysis (Marquard et al. 1995) to provide a method of biochemical verification. To aid cultivar identification, color photographs of many accessions of the cultivar collection are available on the internet at the site maintained by the USDA Pecan Breeding Program and the Georgia Breeding Program (http://extension-horticulture.tamu.edu/carya) and (http://www.caes.uga.edu/commodities/fruits/pecanbreeding/). Photos are color standardized (Thompson et al. 1996) and are linked to specific inventory trees for which additional evaluation information is available. In addition, the site provides passport information for the most commonly planted cultivars.

Collections of other *Carya* species are maintained either as grafted trees (in the case of selected hickory cultivars) or as own-rooted trees (in the case of native tree collections). Currently, all hickory cultivars maintained in the repository are available from commercial sources and have not been distributed. Seed collected from native trees has been sent to researchers, but seedlings in repository collections are still juvenile and are not disseminated. The collection provides an excellent foundation for the study of diversity in this genus. Some accessions are maintained of the sister genera Annamocarya, Juglans, Pterocarya, and Platycarya, providing resolution for the study of diversity in the Walnut Family, Juglandaceae.

Other collections of pecan and hickory exist in the USA and other countries (see Bettencourt and Konopka 1989). Notable US collections include (1) Southeastern Fruit and Tree Nut Lab, Byron, Ga., (2) Coastal Plain Experiment Station, Tifton, Ga., (3) Pecan Experimental Field, Chetopa, Kan., (4) Northern Pecan Research Planting, University of Nebraska, Lincoln, Neb., (5) Pecan Research-Extension Station, Louisiana State University Agricultural Center, Shreveport, La., (6) Alabama Pecan Collection, Fairhope, Ala, and (7) Pecan Provenance and Hybridity Test, Louisiana State University, Idlewild, La. Most collections of *Carya* in other countries are small collections of named US cultivars. Notable exceptions include (1) a collection of cultivars and seedlings of several US *Carya* species and interspecific hybrids, maintained at the Holden Arboretum, Kirtland, Ohio, (2) a collection of *C. laciniosa* from Canada, maintained at the University of Guelph Arboretum, Guelph, Ontario, Canada, and (3) a collection of commercial cultivars and landraces of pecan maintained at the Campo Agricola Experimental de La Laguna, Matamoros, Torreon, Mexico.

Major sources of superior genetic characteristics for nut quality and productivity are provided by superior new cultivars and selections produced in the USDA and the UGA (University of Georgia) breeding programs. These selections represent the forefront to pecan genetic improvement, but new selections are still only a few generations removed from wild trees.

Other potential sources of useful quality traits are provided by experienced growers who discover chance seedling trees with valuable characteristics. Traits which are commonly selected by growers include the following: high kernel percentage, early harvest date, large nut size, and resistance to scab. The UGA breeding program regularly trials grower selections and occasionally makes use of them as parents in the breeding program. Since most seedling trees developed from nuts from popular cultivars, these genotypes can have many favorable quality traits. However, long-term evaluation in replicated orchards often reveal flaws that prevent their use as new cultivars.

A plethora of diseases, insects, and mites attack pecan (Tables 20.2 and 20.3). Host plant resistance to diseases, especially scab, has been observed in many improved cultivars and native populations in the more humid pecan production areas (Table 20.4). Pecan clones exist in Louisiana on which scab has never been observed, even though they are grown in high scab environments (Goff, personal communication). However, the presence of a large number of scab races has been demonstrated, and most pecan cultivars, even those that are highly susceptible, have

Table 20.2 Pecan diseases of the USA and area of occurrence

Common name	Scientific name	Geographic area of occurrence
Fungi		
Scab	*Cladosporium caryigenum* (Eli. et Lang) Gottwald [=Fusicladium effusum (Wint.)]	E. of 98 Longitude
Vein spot	*Gnomonia nerviseda* Cole	Most production areas E. of C. Tex
Downy spot	*Mycosphaerella caryigena* Demaree and Cole	Most production areas E. of C. Tex.
Liver spot	*Gnomonia caryae* Wolfe var. pecanae Cole	Most production areas E. of C. Tex
Zonate leaf spot	*Cristulariella pyramidalis* Waterman and Marshall	Most production areas E. of C. Tex
Powdery mildew	*Microsphaera alni* de Candolle ex Winter	Most production areas
Pink mold	*Cephalothecium roseum* Corda	Most production areas E. of C. Tex
Leaf blotch	*Mycosphaerella dendroides* (Cooke) Demaree and Cole	Most production areas E. of C. Tex
Brown leaf spot	*Cercospora fusca* Rands	Most production areas E. of C. Tex
Clitocybe root rot	*Clitocybe tabescens* (Scop. ex Fr.) Bres.	Ga. and possibly other S.E. states
Phymatotrichum root rot	*Phymatotrichum omnivorum* (Shear) Duggar	C. Tex. and W
Bacteria		
Crown gall	*Agrobacterium tumefaciens* E.F. Smith and Townsend	All production areas
Bacterial Leaf Scorch	*Xylella fastidiosa*	All production areas
Unknown cause		
Shuck dieback		Most production areas
Stem-end blight		Red River and Mississippi River Valleys
Tumor disease		Humid Red River and Mississippi River Valleys
Bunch disease		Most production areas

Table 20.3 Pecan insects and mites in North America

Common name	Scientific name
Pecan nut casebearer	*Acrobasis nuxvorella* Neunzig
Hickory shuckworm	*Cydia caryana* Fitch
Pecan weevil	Curculio caryae Horn
Black pecan aphid	*Melanocallis caryaefoliae* Davis
Black margined aphid	*Monellia caryella* Fitch
Yellow hickory aphid	*Monelliopsis pecanis* Bissell
Pecan phylloxera	*Phylloxera devastatrix* Pergande
Pecan leaf phylloxera	*Phylloxera notabilis* Pergande
Southern pecan leaf phylloxera	*Phylloxera russellae* Stoetzel
Lesser pecan leaf phylloxera	*Phylloxera texana* Stoetzel

(continued)

Table 20.3 (continued)

Common name	Scientific name
Pecan budmoth	*Gretchena bolliana* Slingerland
Southern green stinkbug	*Nezara viridula* L.
Brown stinkbug	*Euschistus servus* Say
Fall webworm (2 races)	*Hyphantria cunea* Drury
Pecan leaf casebearer	*Acrobasis juglandis* LeBaron
Pecan cigar casebearer	*Coleophora laticornella* Clemens
Pecan nursery casebearer	*Acrobasis caryivorella* Ragonot
Walnut caterpillar	*Datana integerrima* Grote and Robinson
Serpentine leaf miner	*Stigmella juglandifoliella* Clemens
Upper southern leaf miner	*Cameraria caryaefoliella* Clemens
Lower southern leaf miner	*Phyllonorycter caryaealbella* Chambers
Pecan leaf scorch mite	*Eotetranychus hicoriae* McGregor
Top leaf southern. mite	*Oligonychus viridis* Banks
Vein mite	*Brevipa1pus* sayedi Baker
Leaf roll mite	*Aceria caryae* Keifer
Pecan catocala (several spp.)	*Catocala maestosa* (Hulst) and C. spp.
May beetles (l5 spp.)	*Phyllophaga* and *Anomala* spp.
Plant hoppers (4 spp.)	*Anormenis septentrionalis* Spinola and others
Myriads (3 spp.)	*Orthotylus ramus* (Knight) and others
Cicadas (2 spp.)	*Magicicada septendecim* L.
Hickory horned devil	*Citheronia regalis* F.
Sawfly	*Periclista marginicollis* Norton
	Megaxyela major Cresson
Obscure scale	*Melaspis obscura* Comstock
Hickory shoot curculio	*Conotrachelus aratus* Germar
Shoot curculio	*Conotrachelus pecanae*
Nut curculio	*Conotrachelus hicoriae* School
Cambium curculio	*Conotrachelus anaglypticus* Say
Red shoulder, shot hole borer	*Xylobiops basilaris* Say
Pinhole borer	*Xyleborus affinis* Eichhoff and others
American plum borer	*Euzophera semifuneralis* Walker
Flat headed appletree borer	*Chrysobothris femorata* Oliver
Banded hickory borer	*Knulliana cincta* Drury
Pecan borer	*Conopia scitula* Harr.
Pecan carpenter worm	*Cossula magnifica* Strecker
Oak pruner	*Hypermallus villosus* Fab.
Twig girdler	*Oncideres cingulata* Say
Giant bark aphid	*Longistigma caryae* Harris
Leaf-footed bug	*Leptoglossus phyllopus* L.
Northern leaf-footed bug	*Leptoglossus oppositus* Say
Pecan spittle bug	*Clastoptera achatina* Germar
Alder spittle bug	*Clastoptera obtusa* Say
Tile-horned Prionus	*Prionus imbricornis* L.
Broad-necked Prionus	*Prionus laticollis* Drury
Termites	*Reticulitermes* spp.

Table 20.4 Sources of genes for pest resistance in *Carya*

Pest	Resistant cultivars or clones	References
Diseases		
Fungi		
Cladosporium caryigenum	Deakle's Special, Dixie, Elliott, Gafford, Gloria Grande, Melrose, Sumner, Pioneer, USDA 61-6-67, USDA 56-6-148	Goff et al. (1993)
	Barton, Buchel I, Curtis, USDA 88-7-1	Goff et al. (2003)
	A-1, Bradley (or Bradley-2?)Cs-14, Cs-60, Elliot, Gloria Grande, Enloe, Pseudocarman, Russell	KenKnight (1968a, b)
	Barton, Candy, Curtis, Davis, Elliott, Farley, Gloria Grande, Jackson, Melrose, Peruque, Sumner	Hunter et al. (1986)
	Curtis, Dependable, Elliott, Gloria Grande	Payne et al. (1979)
Gnomonia nerviseda	Curtis, Choctaw, Mahan	KenKnight (1968a)
	Barton, Cape Fear, GraBohis, Jackson, Maramec, Mohawk, Sumner	Hunter et al. (1986)
Mycosphaerella caryigena	Jennings Elliott, Wichita	KenKnight (1968a), Hunter et al. (1986)
Gnomonia caryae var. *pecanae*	Carman, Curtis, Desirable, Gloria Grande, Jackson, Jennings, Moreland, Russell, Superdesirable	KenKnight (1968a)
Mycosphaerella dendroides	Most clones resistant, except Desirable	KenKnight (1968a)
Cercospora fusca	Carman, Candy, Curtis, Gloria Grande, Moreland, Natchez, Russell, A-93	KenKnight (1968a)
Cephalothecium roseum	Those clones resistant to scab	Payne et al. (1979)
Microsphaera alni	Most resistant, except Caspiana, Pabst, Superdesirable	KenKnight (1968a)
From unknown causes		
Shuck dieback	Success is susceptible	Payne et al. (1979)
Stem-end blight	Most cultivars seem resistant, except Success, Dunstan, Magenta, Barton, Desirable	Payne et al. (1979)
Bunch disease	Candy, Choctaw, Curtis, Farley, Gloria Grande, Jackson, Lewis, Mohawk, Stuart	KenKnight (1968a)
Tumor disease	Desirable, Stuart	Payne et al. (1979)
Leaf scorch	Barton, Choctaw, Curtis, Desirable, GraBohls, Kiowa, Maramec, Mohawk, Shawnee	Hunter et al. 1986
Insects/mites		
Cydia caryana	USDA Selections 44-15-51 and 44-4-135, Osage, GraBohls, Cape Fear, Chickasaw, Cherokee, Shoshoni, Brake	Calcote et al. (1976), Hansen et al. (1970)
Curculio caryae	Success, Mobile, Teche, Van Deman, Nugget, Mahan, Schley	Moznette (1948), Criswell et al. (1975), Boethel and Eikenbary (1979), Gill (1917)

(continued)

Table 20.4 (continued)

Pest	Resistant cultivars or clones	References
Hemipterans	Candy, Creek, Forkert, Grabohls, Gloria Grande, Kanza, Kiowa, Maramec, Owens, Pawnee, Sumner, Tejas, Western Schley	Dutcher et al. (2001)
Melanocallis caryaefoliae	Curtis, Moneymaker, Moore	Moznette et al. (1940)
	Cape Fear, Creek, Kiowa, Pawnee, Schley	Kaakeh and Dutcher (1994)
	Barton, Cape Fear, Cowley, Curtis, Farley, Grabohls, Mahan, Sioux	Wood and Reilly (1998)
Monellia caryella	Success, Schley	Carpenter et al. (1979)
	Gloria Grande, Pawnee	Kaakeh and Dutcher (1994)
Monelliopsis pecanis	Cape Fear, Pawnee	Kaakeh and Dutcher (1994)
Phylloxera notabilis	Delmas, Western Schley, 1983 Williamson, Success, Squirrel's Delight, Stuart Moneymaker, Burkett, plus many others	Boethel et al. (1976), Calcote (1983)
Phylloxera devastatrix	Many	Calcote and Hyder (1980)
Clastoptera achatina	Stuart, Lewis, Mahan	Neel et al. (1976)
Tetranychidae	Stuart	Gentry et al. (1976)
Boarmia selenaria	Moneymaker, Mahan, Schley	Wysoki and Yizhar (1976)

resistance to multiple scab races (Conner and Stevenson 2004). As a result, when newly selected clones displaying strong scab resistance at a single location are propagated and distributed on a wide scale, resistance often breaks down as they are exposed to a larger number of scab races (Goff et al. 1998; Thompson et al. 1995). Resistance to other diseases has been observed in many sources, but verification is lacking (Table 20.4).

The black pecan aphid *Melanocallis caryaefoliae* (Davis) and the yellow aphid complex [the black margined aphid. *Monellia caryella* (Fitch) and the yellow pecan aphid (*Monelliopsis pecanis* Bissell)] are major entomological pests of pecan. Several studies of host plant resistance to these aphid species have been undertaken (Table 20.4). Breeding for resistance to aphids is an integral part of the current pecan breeding programs, but is complicated by the fact that cultivars preferred by one aphid species are not necessarily preferred by another aphid species (Kaakeh and Dutcher 1994). Some cultivars do, however, seem to have resistance to more than one species. 'Pawnee' has been shown to have a high level or resistance to the yellow pecan aphid complex (Kaakeh and Dutcher 1994; Thompson and Grauke 1998; Thompson et al. 2000), and 'Cape Fear' appears resistant to black and yellow pecan aphids (Kaakeh and Dutcher 1994). A major source of the damage caused by the yellow pecan aphid complex is caused by the deposition of honeydew on leaf surfaces which leads to the growth of a fungal mat on the leaf surface which reduces photosynthesis (Tedders and Smith 1976). Adherence of this fungal mat appears to be controlled by leaf surface morphology which varies among cultivars (Sparks and Yates 1991). Sources of resistance to many other insects have been little studied, and most putative sources of resistance need to be validated (Table 20.4).

4 Major Breeding Achievements

There have been three foundation breeding locations for genetic improvement of pecan scion cultivars: Jackson County, Mississippi; San Saba County, Texas; and the USDA Pecan Breeding Station at Brownwood, Texas (Crane et al. 1937; Thompson and Grauke 1991).

Jackson County cultivars were the result of selections made by several area nurserymen and included 'Stuart,' 'Schley,' 'Desirable,' 'Success,' 'Pabst,' and 'Forkert' (KenKnight 1970). The first person to attempt controlled pollinations of pecan was C. Forkert of Jackson County, who planted seed from his first controlled crosses in 1903 and is responsible for 'Desirable' ('Success' × 'Jewett') and 'Forkert' ('Success' × 'Schley') (Forkert 1914). Jackson County cultivars have dominated orchards in the Southeast since the late 1800s.

E.E. Risien of San Saba County, Texas, was the first person to conduct a systematic survey of wild pecans for seedlings worthy of propagation (Crane et al. 1937). Around 1882, Risien discovered the tree that he later propagated as 'San Saba.' An orchard planted using nuts of 'San Saba' produced the trees 'San Saba Improved' and 'Squirrel's Delight' (Crane et al. 1937). Risien used controlled pollinations to produce the cultivars 'Banquet' ('Sovereign' × 'Attwater') and 'Commonwealth' ('Longfellow' × 'Sovereign'). He developed improved pecan propagation techniques during the 1890s and was a pioneer in top-working large pecan trees (Crane et al. 1937). A particularly significant contribution was his introduction of the technique of grafting juvenile buds from controlled crosses into large bearing trees to reduce the period of juvenility (Romberg and Smith 1950).

The third pecan cultivar "nursery" has been the USDA Pecan Breeding Program at Brownwood, and College Station, Texas. The program was initiated by L.D. Romberg, who worked from 1931 to 1968. The program was continued by G.D. Madden (1968–1977), and T.E. Thompson (1979–present). Early breeding objectives included increasing nut size, percent kernel, ease of shelling, scab resistance, and many minor genetic traits. Scab resistance screening was very limited due to lack of humidity and scab pressure at Brownwood, but many crosses of resistant parents produced progenies that were sent for evaluation in Louisiana and other higher scab pressure areas. This program released improved pecan cultivars for all pecan growing regions. Some cultivars were scab resistant, and could be grown in both southeastern US environments and western locations, while some cultivars were very susceptible to scab, and were released as "western cultivars." Few northern US cultivars were released until recently.

'Mahan' and 'Schley' have been the most productive parents used in the USDA program, in existence since ca. 1930. Each of these cultivars parented of six of the 26 USDA cultivars (Table 20.7). Both parents have a very thin shell, which leads to a high kernel percentage. Other commonly used parents include 'Success' which has a thin shell, 'Mohawk' which is large and early ripening, and 'Evers' which is very prolific and thin shelled. Cultivars released by the program are steadily gaining popularity, with many nurseries, especially in the south central region, selling mostly improved cultivars from this program. Highly popular recent releases from

Table 20.5 Rootstocks used in different US states (Thompson 1990)

State	Cultivar
Alabama	Elliott, Curtis, plus others
Arizona	Riverside and many others
Arkansas	Mainly natives
California	Riverside, Apache, VC1-68, plus others
Florida	Elliott, Curtis, Waukeenah, plus others
Georgia	Elliott, Curtis, plus others
Kansas	Giles, plus natives
Kentucky	Natives
Louisiana	Stuart, Moore, Elliott, Desirable, Candy, natives, plus others
Mississippi	Owens, Big Dan, Moore, water hickory
Missouri	Mainly natives
New Mexico	Riverside, Burkett
North Carolina	Cape Fear, plus others
Oklahoma	Riverside, Apache, Giles, plus others
South Carolina	Curtis, Stuart, Elliott
Tennessee	Gerardi, plus natives
Texas	Riverside, Apache, plus many others

this program include 'Pawnee,' 'Oconee,' 'Kanza,' and 'Creek.' 'Hopi,' 'Nacono,' 'Waco,' and 'Lakota' are more recent releases which are expected to gain popularity as growers become familiar to them.

Success in the improvement of pecan rootstocks has been mainly the identification of scion clones that produce superior half-sib and full-sib open pollinated populations of seedlings that are vigorous enough to be easily propagated to good scion cultivars, and at the same time are adapted to high-salt soils of the west or other specific industry requirements. Nurseries grow their pecan rootstocks from open-pollinated seed of favorite scion cultivars (Table 20.5). The seedlings from these families are genetically highly variable and produce many inferior seedlings that are nonvigorous and that must be removed prior to scion propagation. Techniques to produce clonal rootstocks have been attempted without commercially useful results (Gossard 1941; Romberg 1942, 1967; Pokorny and Sparks 1967; McEachern 1973; Gustafson 1978; Hansen and Lazarte 1984). Although rooted ramets have been produced by juvenile and adult phase cuttings, layerage, and in vitro techniques, ramets generally express low vigor and survival. The ramet trees generally lack the ability to establish a vigorous root system, and decline over time.

The objective of the nurserymen is to select a rootstock source (scion cultivar) that will produce a large proportion of rapidly growing seedlings. Seedling height, and especially lower trunk diameter (where most propagation occurs), are of prime importance. There is a recognized need for salt-resistant rootstocks for orchards west of central Texas. 'Riverside,' 'Burkett,' and 'Apache' are widely used in this area.

In the central and western USA, scions are propagated onto the seedling rootstocks mainly by patch budding, while in the eastern USA, many trees are whip grafted at or just below soil level. Traditionally all pecan orchards were established with bare root trees, but container grown trees are gaining popularity.

Container trees offer greater uniformity of establishment, and can be grown in nonsoil media if needed to circumvent soil import restrictions into western states.

The USDA rootstock breeding program is currently identifying parental material with low harmful ion uptake (sodium and chlorine), and high zinc uptake. The goal is to identify superior clones that can be released to serve as parents for open-pollinated seedling rootstocks. These superior clones would need to be grown in isolation to allow interpollination, and exclude other pollen sources. Controlling the male parentage in this way would add greatly to the genetic uniformity and value of rootstock seedlings.

There is a strong need in the pecan industry for a breeding program to produce synthetic populations of rootstock seedlings. This has never been attempted in pecan, except perhaps by E.E. Risien who had somewhat of a rootstock breeding program. 'Riverside' is a superior producer of rootstock seedlings, and is traceable to Risien's early work. This clone resulted from a scion tree that was transplanted, and when the scion died, it was replaced by rootstock growth. A rootstock breeding program should follow traditional synthetic crop breeding techniques with diligence given to shortening the sexual generation time using techniques outlined below. Inbreeding depression is very common when pecan is selfed, so simple recurrent selection should be used (Allard 1966).

5 Current Goals/Challenges of Breeding

Pecan is diploid ($n=16$), anemophilous, monoecious, and heterodichogamous. In pecan, male and female flowers are produced at different locations on the same tree. On each clone (cultivar), the male or the female flowers mature first (heterodichogamy). The complete heterodichogamy of pecan makes it almost completely cross-pollinated, resulting in high heterozygosity with severe inbreeding depression when selfed. Hybrid vigor has been selected naturally in the evolution of this species. Survival of pecan in its native environment depended greatly on growth potential. Therefore, it seems to be a naturally vigorous, wood-producing tree.

From a breeding standpoint, we know less about tree crops than agronomic crops, which are usually annuals. The reason for this greater knowledge of agronomic crops is that they lend themselves to breeding research, whereas tree crops have much longer generation times. It seems, however, that techniques for improvement through breeding may be equally effective in tree crops and annual agronomic crops, especially if compared on a generation basis. The genetic improvement of pecan is impressive considering that only one to five cycles of controlled crossing have been used. In other crops, breeding cycles usually mean more than one generation and usually involve selfing. In pecan a single improved clone takes years to test, but during this testing phase, plants are genetically stable since the genes of the clone are fixed and the trees are clonally propagated. As a result, genetic variability is zero in evaluation trials. This contributes greatly to the effectiveness of testing clonal fruit and nut crops like pecan.

As mentioned earlier, pecan is diploid. Genetically, this makes selection more direct for both qualitative and quantitative characters. Hopefully, we can determine segregation ratios for more simply inherited traits in the future. For example, a single gene determines the type of dichogamy in pecans (Thompson and Romberg 1985). This knowledge is used to produce either protandrous or protogynous clones in the breeding program as needed. There may also be specific genes conditioning resistance to different races of the scab organism. The inheritance of many other traits such as precocity, length and time of season of nut fill, and some insect-resistance mechanisms is probably quantitative.

Basic research related to the breeding program consists mainly of techniques to improve breeding efficiency and expand the genetic knowledge of pecan. One of the most direct needs is a technique to induce early flowering in juvenile clones at perhaps 2 or 3 years of age. Currently, most pecan seedlings flower at 6 or 7 years of age. Early pistillate flowering on 15-month-old clones (time of germination to pistillate flower production) has been accomplished (Thompson 1986). The frequency, however, was low, and to be useful as a breeding technique, the frequency must be greatly increased. Early juvenile flowering has been accomplished in some other tree species, but specific techniques to routinely induce female flowering in pecan has not been developed. The benefits of such techniques are obvious in selection programs to radically alter gene frequencies which control important traits, such as yield, nut maturity time, and disease and insect resistance.

Pecans are considered by some to be a relatively inefficient food production crop. We feel the main reason for this is its late nut-filling period. The pecan kernel begins to form about August 1 in early nut maturing cultivars like ‘Pawnee’ and ‘Kanza.’ This is a period of the year when days are shorter (less light for photosynthesis), the leaves have been damaged by insects and diseases all season, the roots are competing with the nuts for photosynthate to replenish root carbohydrate reserves for winter and spring growth and flowering, and perhaps soil moisture and nutrients have been exhausted by 6 months of active growth. This heavy masting effect late in the season also induces the absence of flower production the following spring which produces the alternate bearing syndrome in pecan. Perhaps this alternate cycle was needed in the wild to escape nut feeding insects, but it is definitely not needed in improved orchards.

The basic consideration here is that the pecan tree is designed wrong for maximum nut production. It is too much of a forest tree designed to effectively compete with other species for space in forest canopies. This is mainly related to fast vegetative growth which is needed for competitive survival in the wild, but exactly what is not needed in developed orchards where competition is artificially removed. The idea is to direct more photosynthate into the earlier production of nuts and less into the production of unneeded wood.

Late nut development in pecans may have resulted from selection induced by animals feeding on the earliest-maturing nuts. This effect is obvious in stands of clones, some of which mature early. These nuts are completely destroyed by feeding animals in the area. Clones with nuts maturing later partially escape this severe feeding pattern, and a portion of the nuts are stored underground by squirrels or

otherwise allowed to germinate the following spring. It is interesting that pecan is one of the latest species, as far as developing nuts, in the *Carya* genus.

The nut-filling period may also be too short in pecan. Lengthening this period in some other crops has improved yield ability. We are accumulating data on this trait now and it may be related to yield.

The xenia effect or the immediate effect of the pollen on nut filling and development is also being determined. The presence of this pollen source effect on nut development in species related to pecans has been documented. In pecan pollen from some cultivars reduces premature nut sprouting or vivipary. We need to determine the value of the xenia effect so that specific cultivar recommendations can be made that maximize productivity and nut size when new orchards are established

A need to control or reduce tree size is generally recognized in pecan. There have been some past references in pecan literature to dwarf varieties that are currently available. For example, Cheyenne is sometimes considered "dwarf-like." This terminology is unfortunate because Cheyenne and some other clones are only slower-growing, and are not really dwarf-like at all. Whether tree size can be reduced most effectively by discovering and using dwarfing rootstocks or by developing dwarfed cultivar (scion) clones is debatable. There are advantages to each. In Persian walnut production in California, small tree size results from genetic characteristics of the scion growing on a very vigorous rootstock. This should also work in pecan production. In any event, hopefully future cultivars will be partially dwarfed by high nut production which will limit the photosynthate available for vegetative growth in the spring when most shoot extension growth occurs.

Heritability studies of genetic traits are also conducted as part of the breeding program. This knowledge allows the effectiveness of the breeding program to be improved by more accurate prediction of how many clones of each cross will be discarded due to inadequate yield potential, nut size, disease resistance, or other trait.

Pecans are attacked by a wide range of disease and insect pests causing substantial losses to the crop. In the humid growing conditions of the southeastern USA, the most economically damaging of these is pecan scab, caused by the fungus *Cladosporium caryigenum*. Foliar infections result in black circular lesions that under favorable conditions can result in severe leaf spotting, premature defoliation, and shoot death. Development of lesions on fruit shucks reduces yield and nut quality, and if not controlled it can result in total crop loss. Commercial pecan plantings in the southeastern USA may require up to 11 fungicide applications annually to control the disease (Ellis et al. 2000). Pecan scab has developed resistance to at least two separate classes of common fungicides (Stevenson 2005). The development of scab resistant cultivars with excellent commercial quality would greatly increase the profitability of pecan cultivation in the Southeast and is the focus of several cultivar development programs (Conner 1999; Goff et al. 1998; Thompson and Grauke 1994).

It is useful to study the history of pecan scab to better understand how to approach the development of scab resistant cultivars. In their 1929 paper, Demaree and Cole provide an interesting review of the history of pecan scab in the Albany, Ga., region.

Prior to 1910, scab was considered a relatively minor disease, of spotty incidence, primarily affecting seedlings or a few cultivars. Before 1920, the authors state that 'Georgia' was the only cultivar generally affected by scab. Beginning in 1920, however, 'Delmas' began to be affected, and in 3 years the fungus had spread to the entire region and became a serious problem on this cultivar. At the same time, 'Alley' also began to be affected. In 1923, 'Schley' began to be affected in Putney and Baconton Ga., located to the south of Albany. From there it spread so rapidly that by 1926 it had become extremely destructive throughout the region. In 'Van Deman' the amount of scab slowly increased during the 1920s and was causing some damage under favorable conditions. 'Pabst' was still free of the disease in Albany at the time the article was written. In contrast, in Ocean Springs, Miss., 'Pabst' was very susceptible but 'Schley' was relatively free of the disease. In a Louisiana orchard, 'Pabst' and 'Moneymaker' were scabbing, while trees of the very susceptible cultivars 'Delmas' and 'Georgia' were unaffected.

Two facts stand out from these early reports on scab incidence: (1) cultivars now considered quite susceptible, such as 'Schley' and 'Alley,' were at one time little affected by scab, and (2) cultivars can vary in susceptibility depending upon location. Both of these factors are explained by the existence of multiple races of the fungus. Indeed, the presence of multiple races of the scab fungus has been demonstrated experimentally by several authors including Demaree and Cole (1929) and Converse (1960).

Even with the pessimistic situation presented above, there are still many opportunities for a breeding program to assist in the control of this disease. Many new cultivars seem to have a grace period during which they are relatively free of the disease. For some cultivars, this period is relatively short, and for others it has lasted decades. By testing new selections in several locations breeders can hopefully select cultivars whose resistance will not be overcome quickly. An active breeding program can take advantage of this grace period by producing a continual supply of new cultivars. This will assist growers by giving them an opportunity to plant a new cultivar with new resistance genes when they turn over an orchard. Hopefully, by the time a current cultivar has become extremely susceptible to scab, there will be new cultivars with different resistance genes ready to replace it. Thus, the overall level of disease decreases and becomes more manageable. If resistant selections have nut quality equal or superior to the standard susceptible cultivars, then loss of resistance once it happens need not be catastrophic. Growers would begin controlling scab using the methods they use on susceptible varieties, and eventually rotate to newer resistant varieties when replanting.

Other projects include developing DNA markers for resistance genes and examining the physiological basis of scab resistance. DNA markers for scab resistance genes will be very useful in a breeding program. They will allow us to quickly identify resistance genes in our seedling progenies without laborious inoculation procedures. They may also allow us to pyramid multiple resistance genes into a single cultivar. Resistance based on several different resistance genes may be more difficult for the scab fungus to overcome and thus be more durable in the field. Currently we understand very little about how pecan protects itself from scab infection.

By studying the infection process microscopically, we hope to better understand this process and use this knowledge to select trees with higher levels of resistance.

Various levels of resistance to scab are available in pecan germplasm. However, few cultivars contain sufficient resistance so that fungicide applications are not necessary and these usually lack many of the nut quality traits desirable for commercial plantings. In addition, many important high quality cultivars such as 'Stuart' and 'Desirable' are becoming increasingly susceptible to the scab pathogen, due at least partly to the presence of multiple races of the fungus (Thompson and Grauke 1994). As a result, commercial pecan plantings require 8–11 applications of fungicides to remain profitable. Pecan scab has developed resistance to at least one common fungicide, Benlate. In addition, concern over negative environmental health effects of pesticides has resulted in pressure to increase regulation of other valuable chemical control agents. Development of varieties with combinations of disease and insect resistance would result in further savings. Resistant varieties could also reduce risks of epidemics when weather conditions are favorable for disease growth and unfavorable for pesticide application. The development of resistant cultivars will play a vital role in maintaining the profitability of pecan culture in the Southeast.

The basis of scab resistance in pecan is not well understood at the genetic level. In the only large-scale analysis of inheritance of scab resistance, Thompson and Grauke (1994) evaluated 948 seedlings derived from 15 controlled crosses for the presence of nut scab. Seedlings were grown in an unsprayed orchard at Brownwood, Texas, and evaluated for nut scab from naturally occurring infections in a year of high disease incidence. The heritability of resistance was determined by regressing progeny scab rating values on male, female, and midparent values. Midparent values gave the highest correlation (0.54) indicating a moderate level of additive gene action. This work also indicated that certain cultivars such as 'Gloria Grande' may transmit a higher level of scab resistance to their progeny, making them superior parents.

One of the most important factors to be considered by any breeding program aimed at producing resistant cultivars is the presence of multiple races of the scab pathogen. Many cultivars that were once highly resistant to scab are now widely considered susceptible. For example, the cultivars 'Desirable' and 'Stuart' are grown throughout the Southeast and were initially popular at least in part due to their high levels of scab resistance. Both cultivars are now commonly considered susceptible and the appearance and spread of a race of scab capable of infecting 'Stuart' was documented (Cole and Gossard 1956).

The presence of multiple races of the scab pathogen has been inferred from the wide range of scab susceptibility cultivars demonstrate when grown in different geographic locations (Sparks 1992; Demaree and Cole 1929). Demaree and Cole (1929) used orchard inoculations to demonstrate that at least four races of the pathogen exist which differ in their ability to infect cultivars. Converse (1960) further demonstrated the presence of four races on the basis of their pathogenicity in greenhouse and field tests on four pecan cultivars. In a recent study conducted in this laboratory, four scab isolates were inoculated onto each of the four cultivars from which they were isolated (Conner 2002). Detached leaves were then examined

Table 20.6 Summary of detached-leaf reactions of four pecan cultivars inoculated with *Cladosporium caryigenum* isolates from each of the same four host cultivars

	Scab isolate tested			
Cultivar tested	Wichita isolate	Desirable isolate	Cape Fear isolate	Elliot isolate
Wichita leaf	++	–	–	–
Desirable leaf	–	++	–	–
Cape Fear leaf	–	–	++	++
Elliot leaf	–	–	–	+

++ = 30–60% of conidia form subcuticular hyphae; + = 10–15% of conidia form subcuticular hyphae; – = <5% of conidia form subcuticular hyphae

microscopically to determine the susceptibility of each cultivar to each isolate. Scab isolates differed in their ability to form subcuticular hyphae on the different cultivars, with the greatest amount of infection usually occurring when the isolate was placed back onto the cultivar from which it was isolated (Table 20.6). The cultivars in this test were generally highly resistant or immune to isolates from other cultivars. It is apparent from these studies that a range of genetic types of the pathogen exist and these differ markedly in their ability to cause disease on different pecan cultivars.

With this information in hand, the next question becomes how is resistance inherited in the progeny resulting from crosses between pecan cultivars with differential resistance to scab isolates? Testing with known isolates will allow us to further refine our knowledge of the inheritance of resistance by avoiding the two most common complications of previous studies (1) the possibility of escapes due to inadequate or variable inoculum and (2) variability in the genetic makeup of the inoculum challenging the seedlings. By evaluating resistance of the progeny of crosses between these cultivars to defined isolates of the pathogen the mode of action of resistance genes and their inheritance in the progeny can be determined. This information will be vital to designing future crosses aimed at achieving high levels of resistance in the progeny and for developing molecular marker tags for important resistance genes. This work will also provide information on those cultivars most likely to be useful as parents in breeding new resistant cultivars.

Effective breeding for resistance to *C. caryigenum* requires information on the pathogenic diversity of the fungus. There is a range of pathotypes of *C. caryigenum* exist that differ markedly in their ability to cause disease on different pecan cultivars. The work reported here was undertaken to further examine the extent of pathogenic variation among scab isolates using a larger number of cultivars and fungal isolates. These results may be useful in designing crosses to pyramid resistance genes into a single cultivar or in selecting combinations of cultivars to be included in an orchard.

The USDA-ARS pecan breeding program in concert with the UGA breeding program is conducted cooperatively across the entire US production area and consists of many varied and interrelated activities by breeders, geneticists, horticulturists, pathologists, and entomologists. To date (and in cooperation with state agricultural experiment stations), 26 improved cultivars (Table 20.7) have been

Table 20.7 Cultivars developed cooperatively by the US Department of Agriculture, Agricultural Research Service and cooperators

Cultivar	Parentage[a]	Selection number	Year released	Dichogamy[b]
Barton	Moore × Success	37-3-20	1953	I
Comanche	Burkett × Success	37 -8-22	1955	II
Choctaw	Success × Mahan	46-15-276	1959	II
Wichita	Halbert × Mahan	40-9-193	1959	II
Apache	Burkett × Schley	40-4-1 7	1962	II
Sioux	Schley × Carmichael	43-4-6	1962	II
Mohawk	Success × Mahan	46-15-195	1965	II
Caddo	Brooks × Alley	Philema 1175	1968	I
Shawnee	Schley × Barton	49-17-166	1968	II
Cheyenne	Clark × Odom	42-13-2	1970	I
Cherokee	Schley × Evers	48-22-27	1971	I
Chickasaw	Brooks × Evers	44-4-101	1972	II
Shoshoni	Odom × Evers	44-15-59	1972	II
Tejas	Mahan × Risien 1	44-10-293	1973	II
Kiowa	Mahan × Desirable	53-9-191	1976	II
Pawnee	Mohawk × Starking HG	63-1 6-125	1984	I
Houma	Desirable × Curtis	58-4-61	1989	I
Osage	Major × Evers	48-15-3	1989	I
Oconee	Schley × Barton	56-7-72	1989	I
Navaho	Apalachee × Wichita	74-1-11	1994	I
Kanza	Major × Shoshoni	55-11-11	1996	II
Creek	Mohawk × Western	61-6-67	1996	I
Hopi	Schley × McCulley	39-5-50	1999	II
Nacono	Cheyenne × Sioux	74-5-55	2000	II
Waco	Cheyenne × Sioux	75-5-6	2005	I
Lakota	Mahan × Major	64-6-502	2007	II
Mandan	BW-1 × Osage	85-1-2	2009	I
Apalachee	Moore × Schley	48-13-311	2009	I

[a]First parent is the female. Second parent is the male
[b]I = protandrous and II = protogynous

released. One of these, 'Pawnee,' is probably the most popular cultivar in the world, as far as the number of trees being propagated. The value of this one cultivar equals that of all USDA and UGA breeding program costs many times over. Public funding of pecan breeding research is therefore an excellent investment in the future well-being of our country and the world.

6 Breeding Methods and Techniques

There are two pecan scion breeding programs. The US Department of Agriculture, Agricultural Research Service (USDA-ARS), in cooperation with state agricultural experiment stations, state extension services, and private growers; conducts a

Table 20.8 Pecan selection technique in the USDA Breeding Program

Phase	Description	Years	Number of clones per year	Location or spacing (m)
I	BBP Seed production	1	1,000–2,000	Nuts harvested
II	BBP Scab screening	1	1,000–2,000	Potted seedlings, screenhouse/field
III	BBP Orchard	10	500–1,000	Seedling orchard, 4.6×9.1
IV	NPACTS	10–15	5–10	Grafted orchard, 10.7×10.7

national pecan breeding program headquartered in College Station and Brownwood, Texas. It is directed by the senior author. The University of Georgia also conducts a breeding program for that state that is directed by the junior author. Improved cultivars produced in these two programs are also widely grown in other countries.

A breeding system is used which combines desirable genetic characteristics from the two parents. The parents are controlled crossed, and the resultant seedlings are selected based upon desirable characteristics. Although thousands of seedlings are produced and selected, very few clones are produced that are considered worthy of release as new cultivars.

Considering the heritability estimates for major nut characteristics (Thompson and Baker 1993), and the reasonable probabilities for improvement of other traits, large populations of plants need to be produced. There are two selection cycles in the USDA program: the Basic Breeding Program (BBP) and the National Pecan Advanced Clone Testing System (NPACTS) (Table 20.8). Large numbers of seedlings are produced and eliminated in the BBP based upon highly heritable, easily selected characteristics. Only one or two clones per thousand are considered good enough to advance to NPACTS. For instance, elimination of inferior clones based upon yield, precocity, vigor, scab susceptibility, and nut quality, as well as resistance to insects, can be accomplished in the seedling cycle and continued in NPACTS.

In Phase I, the traditional crossing technique is used to produce up to 4,000 seed each year. Crosses are made at Brownwood and College Station, Texas. This large amount of seed is possible due to improved techniques of tree preparation and care so that each crossed cluster produces more seed. For example, some trees in our crossing program routinely produce two to four nuts per cluster, compared with the average of less than one per cluster a few years ago. All fruit on trees to serve as female parents should be removed early in the growing season of the year before crossing. This insures more and larger clusters at time of bagging. Other obvious cultural techniques such as adequate space for the tree, water, etc. are also needed. Bagged clusters should be pollinated twice, 1 day apart. The first pollination to all bags on each tree should be made when any nonbagged receptive flowers can be found on the tree. This insures that viable pollen is on all receptive bagged pistils throughout the pollination period.

All the seed produced by these hand crosses is stratified, then planted in the greenhouse in December and the seedlings are monitored for vigor and other characteristics. In the spring, the seedlings are placed under scab-susceptible trees and

rated for resistance two or three times during the growing season. After each rating, the leaves are removed so that new scab-susceptible leaves are again produced. In the fall, one third to three quarters of the seedlings are discarded due to scab susceptibility (Phase II).

Planting seed directly into a disease garden or scab nursery should also be effective in eliminating most disease-susceptible clones. As above, this assumes that resistance in juvenile leaves is correlated with resistance in mature-phase leaves. Seedlings can be planted directly in the field under, or close to, disease-susceptible cultivars. Again, several susceptible cultivars need to be included to produce an array of diseases and sufficient races of different diseases. Seedlings can be rated for disease resistance for 2 or 3 years; then, resistant seedlings are replanted or grafted into the BBP, for Phase III evaluation.

Phase III is the initial field selection phase at College Station, Texas for yield, precocity, nut quality, desirable leaf and tree structure, and disease and insect resistance. Although most of these seedling trees are transplanted and grown on their own roots, some of these clones are grafted to pollarded large trees to hasten flowering. Trees grown on their own roots are grown at a relatively close spacing and the elimination of trees begins in the 6th or 7th year based upon precocity, nut size, scab resistance, and other traits. This early elimination allows more room for the more desirable clones to develop and be more adequately evaluated. Only about one or two of these clones are saved per thousand for Phase IV NPACTS testing.

In NPACTS, elite clones from Phase III are grafted into replicated trials across the entire pecan belt for environmental adaptation. These tests are conducted using standard extension recommendations for each test location. Testing is often done cooperatively with growers, state experiment stations, state agricultural extension services and universities. For instance, NPACTS tests are currently established at College Station and Amarillo, Texas, in cooperation with Texas Agrilife Research and Extension Service. Other Texas tests are conducted on private land in cooperation with pecan growers. Clones which perform well in these NPACTS tests are released as new USDA-State unpatented cultivars. A new cultivar could possibly be released every 2–5 years. This means that thousands of clones are screened to produce a single new cultivar. This is realistic from a genetic standpoint when projected heritabilities of different traits are considered. Table 20.7 shows the pedigree and other information for the USDA-ARS/state released cultivars.

In 1999, P.J. Conner initiated a new breeding program for Georgia based at the University of Georgia-Tifton Campus. The UGA pecan breeding program was initiated with the goal of releasing high quality cultivars adapted to the southeast region, and especially the state of Georgia (Conner 1999). Given the prevalence of rain during the growing season in this region, durable scab resistance is a primary objective of this program (Conner 2003). Other traits being targeted include early harvest date, large nut size, and high kernel percentage to capture the profitable gift-pack market. A previous breeding effort based at UGA-Athens Campus by D. Sparks has resulted in the 2008 release of ‘Byrd’ (‘Wichita’ × ‘Pawnee’), an early maturing cultivar with high kernel quality. Several other selections are in the process of being released from this breeding effort.

The UGA pecan breeding program uses methods similar to those of the USDA. Seedlings are grown for 3–4 months in the greenhouse in root pruning flats. In April or May the seedlings are shifted up to 3-gallon root pruning containers and placed outside in a shade house underneath 50% shade cloth. Some sort of root pruning device is highly desirable since pecan has a dominant tap root that will circle a standard pot. The shade cloth is needed to keep seedlings actively growing in the heat of the summer. Starting in June, scabbed branches are cut from a wide variety of cultivars and selections and are rubbed over damp seedlings at dusk. Overhead irrigation is applied intermittently during night to keep the leaves wet. This process is repeated several times over the summer. Seedlings are then rated for leaf scab and, depending upon the progeny, anywhere from 20 to 80% may be eliminated. Seedlings have usually made sufficient growth at the end of the year that they are then planted into fields where they grow on their own roots at a spacing of 3 m between trees within the row and 4.6 m between rows. Seedling trees are monitored for approximately 10 years and superior selections are grafted into trial orchards at Tifton and in grower orchards in Georgia. Superior selections are released as patented cultivars to support the breeding program.

7 Integration of New Biotechnologies in Breeding Programs

The potential of molecular markers to increase our understanding of the pecan genetic diversity has been demonstrated in several studies. Pecan is a newly domesticated crop and many important historical and current cultivars are chance genotypes discovered by nurserymen and growers in seedling orchards or native groves. Understanding the genetic relationships between these cultivars can offer the pecan breeder insights into the best way of producing new favorable combinations of alleles. Protocols for the analysis of five isozyme systems: malate dehydrogenase, phosphoglucose isomerase, phosphoglucomutase, leucine aminopeptidase, and diaphorase have been developed (Marquard 1987, 1989, 1991; Marquard et al. 1995). Using these isozymes, 177 cultivars were sorted into 72 classes and the historical pedigree of some cultivars was called into question. These systems were then used by Grauke et al. (1995) in the evaluation of the pecan germplasm collection to designate a core subset. Conner and Wood (2001) demonstrated the value of randomly amplified polymorphic markers (RAPD) markers in determining genetic relationships among pecan cultivars. Genetic distances, based on the similarity coefficient of Nei and Li, varied from 0.91 to 0.46, with an average of 0.66 among all cultivars. Cerna-Cortes et al. (2003) used AFLP markers to study the genetic diversity of native pecan genotypes from Central Mexico. Genetic diversity in these genotypes was found to be relatively low, probably due to the relatively restricted geographical region sampled. Grauke et al. (2003) developed simple sequence repeats (SSRs) or microsatellite DNA markers and carried out an initial evaluation of SSR markers for use in genetic studies of pecan. The authors found 11 primers that produced polymorphisms among the 48 pecan and hickory accessions, but encountered difficulty in scoring many SSR profiles.

There is a great need in pecan genetics to develop an easy and robust marker system to reliably fingerprint pecan cultivars. Growers often find a few unknown cultivars mixed in with their purchase of grafted trees. These mistakes can come from mistakes in collecting or handling graftwood, mislabeling, or sorting errors of trees in the nursery. It is often difficult to identify these cultivars based on nut phenotype alone. In addition, molecular marker fingerprints could be produced as soon as tissue was available rather than waiting several years for the tree to produce fruit. Molecular fingerprints would also perhaps facilitate tracing the parentage of new seedling cultivars. However, currently developed marker systems in pecan suffer from irreproducibility between laboratories and require technology that is relatively cumbersome for breeding programs to apply on a routine basis.

Molecular marker based maps have the potential to facilitate pecan breeding in two main ways. First, maps can greatly facilitate genetic studies in pecan. Most horticulturally important traits in pecan appear to have a complex mode of inheritance, and genetic maps will allow us to tease apart the individual loci in control of these traits and describe their effects. Second, molecular markers linked to useful traits will facilitate marker-assisted selection of these traits. This is especially important in pecan because of the limitations that long juvenile periods and large plant size place on the number of seedlings that can be grown to fruition. Beedanagari et al. (2005) have produced the only linkage maps of pecan. Because of the outbred nature of pecan, separate maps were produced for both parents of the cross 'Pawnee' × 'Elliott' using a combination of amplified polymorphic DNA (AFLP) and random amplified polymorphic DNA (RAPD) markers. 'Pawnee' is a USDA release which has an exceptionally early harvest date and large, high-quality nut. 'Pawnee' is being used extensively in breeding programs to incorporate early harvest date into new cultivars. 'Elliott' is an older cultivar from Florida which is being used to incorporate scab resistance into new cultivars. The 'Pawnee' map is 2,227 cM in length and is estimated to cover 83% of the 'Pawnee' genome. The 'Elliott' map is 2,965 cM in length and is estimated to cover 57% of the 'Elliott' genome. Two phenotypic traits, dichogamy type and stigma color, were found to be tightly linked and were mapped to linkage group 16 of the 'Elliott' map. Mapping of other phenotypic traits was not attempted due to the young age of many of the progeny trees.

Molecular mapping appears to hold much potential for facilitating pecan breeding. However, the same limitations of large plant size, long juvenile periods, and complex inheritance of most important traits which make molecular mapping so attractive also make it difficult to proceed with the large scale mapping studies needed to produce results which will be useful to the breeding program. Added to these difficulties are the limited funding available to do molecular work in minor crops such as pecan and the severe inbreeding depression which prevents the formation of inbred lines which facilitate the genetic analysis of marker–trait associations. Near-term results are most likely to come from finding markers associated with simply inherited traits which are difficult to analyze phenotypically, such as resistance to pecan scab.

The development of transformation and regeneration protocols for pecan has been limited. Somatic embryogenesis has been accomplished from immature and

mature zygotic embryos of several cultivars (Merkle et al. 1987; Obeidy and Smith 1993; Wetzstein et al. 1989; Yates and Reilly 1990). McGranahan et al. (1993) successfully used a gene transfer system for walnut (*Juglans regia* L.) on pecan. Embryogenic somatic embryos were cocultivated with an *Agrobacterium* strain which contains marker genes for beta-glucuronidase and resistance to kanamycin. Transgenic plants were obtained by grafting tissue cultured shoots onto seedling pecan rootstocks. Initial success in transformation has not been followed up in recent years for several reasons. Consumer acceptance of transgenic pecans is not assured, especially since there are no other transgenic nut crops on the market. Established regeneration protocols make use of zygotic starting material. This is undesirable since pecan cultivars are heterozygous and do not breed true from seed, thus preventing the addition of a transgene into an established cultivar. In addition, pecan is anemophilous, and wild trees exist in the forests surrounding many pecan orchards. This, in combination with nuts carried off by wildlife which can produce new trees, suggests that it would be very difficult to prevent the escape of transgenes into wild populations. The development of transgenic pecans will likely remain limited until methods are developed to overcome these limitations.

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